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EUROPEAN PATENT APPLICATION

(21) Application number: **86101517.0**

(22) Date of filing: **06.02.86**

(51) Int. Cl.⁴: **G 11 B 7/013**
G 11 B 7/24, G 11 B 7/08
G 11 B 7/26
//G11B17/34, G11B23/14,
G11B23/36, G11B23/42,
G11B27/19, G11B7/09

(30) Priority: **11.02.85 US 700735**

(43) Date of publication of application:
15.10.86 Bulletin 86/42

(84) Designated Contracting States:
CH DE FR GB LI NL

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(54) System and method for recording digital information.

(57) A digital recording medium formed of a thermoplastic substrate having a regular array of microscopic optically-alterable mirrors each supported by a mesa projecting from one surface. The parallel rows of the mirrors are the same distance apart as the mirrors in each row. A layer of transparent plastic over the mirrors provides dust protection. The medium can be formed from a single transparent thermoplastic substrate with an array of indentations in a first surface. The bottom of each indentation is coated with a reflective material. When viewed from the opposite surface of the substrate, the indentations become mesas.

Recording is by exposure to a laser beam that reduces the reflectivity of selected mirrors. After exposure to the recording laser beam, the mirrors retain enough reflectivity to be distinguishable from the intervening valleys. The mirrors serve as timing and tracking markers prior to and during recording, and during read-out. The area and location of each information bit is determined prior to recording: not as a result of the recording process. The mirrors are scanned diagonally across the rows that make up the array. Scanning is accomplished by reciprocating movement of the medium.

1 SYSTEM AND METHOD FOR RECORDING DIGITAL INFORMATION

2 Background of the Invention

3 Field of the Invention:

4 This invention relates to digital recording media and
5 more particularly to high capacity recording media for
6 optical recording and read-out.

7 Description of the Related Art:

8 Digital information has been recorded on many kinds
9 of materials by a wide variety of processes. One widely
10 used system magnetizes selected areas of a disk of magne-
11 tic material to represent the information to be preserved.
12 Other approaches, used primarily when greater recording
13 density is desired, include the use of a substrate coated
14 with a material capable of being changed by selective
15 treatment with a laser beam. For example, the substrate
16 may have a reflective surface that is caused to have lower
17 reflectivity in those areas where it is heated by a
18 focused laser beam. Conversely, non-reflecting absorbent
19 surfaces have been rendered reflective by the application
20 of a laser beam as described in Optical Memory News,
21 Sep.-Oct. 1984, page 14. The reflectivity of the surface
22 may be altered by melting or deforming the surface or by
23 actual evaporation of material from the surface. Most
24 often, the medium is in the form of a disk and the infor-
25 mation is recorded along a spiral track. The timing and

1 tracking information may also be recorded by a modulated
2 laser beam following the spiral track.

3 U.S. Patents 4,214,249 to Kasai; 4,270,916 to Dil;
4 4,379,299 to Fitzpatrick et al.; 4,314,262 to Reilly; and
5 4,334,299 to Komurasaki et al. disclose media of the kinds
6 referred to above.

7 The Dil Patent discloses recording on a disk having a
8 grooved spiral and in which timing marks are recorded on
9 the sloping walls of the grooves.

10 The Kasai patent discloses the recording of digital
11 information by the selective exposure to a laser beam that
12 causes deformation or evaporation of a layer composed of
13 S, Se, Te, or chalcogenide compounds thereof. The rate of
14 recording is limited by the heat conductivity of the
15 medium.

16 The Fitzpatrick patent describes a digital writing
17 process in which a film of semiconductor material, such as
18 cadmium telluride, on a substrate of plastic such as
19 methylmethacrylate or polycarbonate, is exposed to a
20 recording laser beam that heats the plastic substrate to
21 produce a pressurized gas bubble that bursts the overlying
22 semiconductor leaving a pit or hole in the reflective sur-
23 face that represents one bit of information. The rate at
24 which information can be recorded is limited by the amount
25 of heat required to cause the eruption and the heat con-
ductivity of the recording medium.

1 The Reilly patent describes a recording medium formed
2 by a thin continuous layer of metal in which bits of data
3 are recorded by alterations produced with focused spots of
4 laser light. A transparent dielectric coating is provided
5 to increase the light absorption of the metal layer.

6 The Komurasaki patent describes a real-time monitor
7 for use with a recording medium comprising a continuous
8 film of metal such as bismuth, gold or chromium which is
9 selectively melted or vaporized by a focused light beam to
10 record one bit of information.

11 U. S. Patent 4,380,769 to Thomas et al. describes the
12 recording of information by the thermal deformation of a
13 continuous thin film of amorphous material carried by a
14 plastic substrate. Individual depressions surrounded by
15 sharply defined ridges are produced in the amorphous film.

16 U. S. Patent 4,334,233 to Murakami describes a dust-
17 protecting shield over the substrate that minimizes infor-
18 mation distortion that might otherwise occur because of
19 dust particles on the recording medium.

20 U. S. Patent 4,428,075 to Hazel describes a prefor-
21 matted disk in which synchronization marks are recorded in
22 areas separate from the data recording areas. These
23 tracking and timing marks are distinct from the altera-
24 tions that represent bits of data and, to the extent they
25 occupy space that could otherwise be used for digital
storage, reduce the capacity of the disk.

1 The formation of arrays having microscopic relief
2 patterns is known in the photographic field where such
3 techniques are used to reduce variations in image density.
4 U. S. Patents 4,366,299 to Land and 4,402,571 to Cowan et.
5 al. discuss the formation of spaced discrete holes using
6 a photoresist that is exposed twice to the interference
7 patterns of two laser beams, one exposure being below the
8 threshold for the development of the photoresist. Land
9 also describes for photographic purposes the formation of
10 peaks coated with silver as one step in formation of a
11 silver halide coating. The structure proposed by Land
12 does not lend itself to the recording of digital infor-
13 mation.

14 U. S. Patent 3,019,124 to Rogers discloses a method
15 of manufacturing photographic elements by applying a first
16 light sensitive layer in a uniform thickness to a support,
17 embossing the coated layer to form a relief impression
18 having systematically arranged spaced elevated sections
19 joined by depressed sections interspersed between them,
20 and applying a second light sensitive layer having a dif-
21 ferent spectral sensitivity to fill the depressions
22 remaining in the surface to the level of raised sections.

23 U. S. Patent 4,362,806 to Whitmore describes a pho-
24 tographic substrate comprising an array of microvessels
25 that are filled with various photographic materials. The

1 object is to reduce lateral image spreading by providing a
2 discontinuous recording substrate. The microvessels are
3 separated only by minute distances that play no part in
4 the recapture of information. Any appreciable thickness
5 of the walls separating the microvessels detracts from the
6 continuous image that is the object of the Whitmore
7 disclosure. The recording is done over mass areas and the
8 microvessel walls are used to prevent undesired lateral
9 spreading of the photographic image. Whitmore suggests
10 electronically scanning the photographic elements to read
11 information in digital format. Whitmore also discloses
12 modifying the microvessels by scanning with a laser beam
13 to alter the character of selected microvessels by
14 melting, sublimation or change in viscosity. The micro-
15 vessels of Whitmore require subsequent photographic pro-
16 cessing to provide optically readable information.

17 Summary of the Invention

18 A digital recording medium has discrete spaced indi-
19 vidually-alterable storage elements which, in one embodi-
20 ment, in the unaltered state, are tiny mirror surfaces,
21 sometimes called here "micromirrors", arranged in a
22 substantially regular array in a plane spaced from a
23 reference plane of a supporting substrate. Each micro-
24 mirror is supported by a mesa extending from the substrate
25 so that the micromirrors are separated by valleys or

1 indentations between the mesas. Each micromirror is indi-
2 vidually optically alterable to store one or more bits of
3 information. The substrate may be protected from con-
4 taminates by a layer of transparent material of substan-
5 tial thickness that minimizes the effect of dust par-
6 ticles. The array of micromirrors is arranged to be
7 scanned by a recording device and subsequently, without
8 further processing, by a reading device.

9 Information is recorded by causing a change in the
10 reflectivity of the selected micromirrors, for example, by
11 subjecting the surface of each selected micromirror to an
12 infrared light beam of sufficient intensity to materially
13 reduce the reflectivity of the mirror. Each micromirror,
14 by having one of two or more levels of reflectivity,
15 becomes a depository for one or more bits of digital
16 information.

17 The regular spacing of the array of micromirrors
18 enables them to serve both as tracking and timing markers
19 prior to and during recording and read-out. In effect, the
20 medium itself acts as an optical encoder for the scanning
21 device. This arrangement permits variations in the
22 scanning velocity, a particular advantage when recipro-
23 cating scanning procedures are used. The micromirrors may
24 be used to control the scanning path, both for recording
25 and read-out, by centering the beam along the path of
maximum reflection.

1 The use of an array of regularly spaced discrete
2 reflective micromirrors makes it possible to test the
3 recording medium for defects prior to recording and
4 authenticate its quality. In a practical way, this elimi-
5 nates the need for monitoring the recording process
6 because the chance of failing to record on a mesa having
7 the required level of reflectivity is small.

8 The reduction in reflectivity of exposed micromirrors
9 results from the absorption of sufficient energy to change
10 the mirror coating itself or to distort the thermoplastic
11 mesa supporting the mirror. The reflectivity of the
12 recorded micromirrors preferably is not reduced to zero,
13 but rather only enough that it can be readily
14 distinguished as a recorded micromirror, the reflectivity
15 of the recorded micromirror remaining greater than that of
16 the valleys separating the micromirrors.

17 In another embodiment, the micromirrors are formed on
18 the bottom surfaces of spaced indentations in a first sur-
19 face of a sheet of clear substrate. Viewed from the
20 second surface of the substrate, the indentations become
21 mesas supporting the micromirrors. The recording and
22 reading light beams are focused on the micromirrors
23 through the second surface of the substrate.

24 In a preferred embodiment, the recorded medium is
25 moved linearly along a full row of micromirrors, while a

1 small transverse oscillation of the read-out light beam
2 maintains the lateral position of the recorded medium such
3 that the read-out beam on the average, tracks the approxi-
4 mate center of the row of mirrors being scanned. At the
5 end of each linear scan, from end to end of the row of
6 micromirrors, the recorded medium is moved laterally one
7 row and then moved linearly in the opposite direction. The
8 arrangement of the micromirrors permits a wide choice in
9 the selection of a particular read-out procedure.

10 Brief Description of the Drawing

11 Figure 1 is an enlarged diagrammatic top view of a
12 small section of a recording medium embodying the
13 invention;

14 Figure 2 is a sectional view along line 2-2 of Figure
15 1;

16 Figure 3 is a partial perspective view of the
17 recording medium shown in Figures 1 and 2;

18 Figure 4 is a reproduction of a scanning electron
19 micrograph of the recording medium of Figures 1-3 at a
20 magnification of 10,000X;

21 Figure 5 is a reproduction of a scanning electron
22 micrograph of an embossed layer of PVC for use in fabri-
23 cating the recording medium;

24 Figure 6 is a reproduction of a photograph of a video
25 image of the medium taken from a video screen at a magni-
fication of 1,750X;

1 Figure 7 shows a section of the medium of Figures 1-3
2 including a transparent protective shield and in which a
3 filler is placed in the valleys between the mirrors:

4 Figure 8 is a partial sectional view of another
5 embodiment of the recording medium in which the protective
6 shield and the substrate are formed integrally from a
7 single sheet of plastic;

8 Figure 9 shows diagrammatically a source of laser
9 light and the associated optics and detectors for
10 recording on and reading from the medium;

11 Figure 10 illustrates diagrammatically a preferred
12 scanning sequence for both recording and read-out; and

13 Figure 11 illustrates the use of the micromirrors for
14 tracking during recording and read-out.

15 Description of the Preferred Embodiments

16 The drawings are not to scale and various elements
17 have been exaggerated for purposes of illustration. In
18 the various figures, similar elements are indicated by the
19 same numerals or by the same numerals followed by an iden-
20 tifying letter suffix.

21 As illustrated by Figures 1-3, a recording medium,
22 generally indicated at 2, in this example, is in the form
23 of a rectangular plastic card about 2 by 3.5 inches which
24 is capable of recording more than 800 megabits of digital
25 information. The medium comprises a substrate or base

1 element 4 having an array of uniformly spaced micro-
2 mirrors 6, each supported by a minute projection or mesa 8
3 extending from one surface of the substrate 4. The pro-
4 jections 8 are integrally formed as part of the substrate
5 4, which may be formed of thermoplastic material, and are
6 separated by valleys, generally indicated at 10.

7 The projections or mesas 8 which support the micro-
8 mirrors 6 serve two functions: to provide thermal isola-
9 tion between adjacent mirrors and to provide a light sink
10 between the mirrors in the form of the valleys 10. The
11 height of the projections 8 above the substrate 4 is not
12 critical and is typically between 0.5 and 2.5 micrometers.
13 The projections 8, in this example, are arranged in the
14 array to provide one storage element for each two micro-
15 meters along each row of mirrors.

16 The thickness of the substrate 4 is not critical but
17 may be of the order of 100 or more times the height of the
18 mesas 8. The mirrors 6, which lie in a common plane, are
19 of material capable of reflecting laser light. Each
20 micromirror is of sufficient size and flatness to function
21 as an effective mirror at the frequency of light being
22 used to read the data from the medium. The mirrors may be
23 formed by coating the tops of each mesa 8 with a layer of
24 reflective material capable of absorbing sufficient energy
25 to permit a low power laser beam to reduce significantly

1 the reflectivity of the micromirror with an exposure of
2 less than about one microsecond. The preferred mirror
3 coating is a composite formed of gold and silicon dioxide.
4 The mirrors 6 should be as flat as possible and the sur-
5 face variations should be limited to a fraction of a wave-
6 length of the incident light, for example, from one-fifth
7 to one-tenth of a wavelength. For the present purposes, a
8 mirror capable of reflecting 20-25% or more of the inci-
9 dent light to be used for readout is defined as a "flat
10 mirror". Each micromirror is capable of immediately
11 detectable alteration, for example, by exposure to a
12 source of focused energy, such as a laser beam, by which
13 is meant the alteration takes place substantially
14 immediately upon such exposure and may be detected without
15 further processing such as is required in photographic and
16 other indirect processes.

17 Preferably, the micromirrors 6 form a regular array
18 as illustrated by Figure 1. By a regular array is meant
19 an array in which the storage elements are equally spaced
20 in parallel rows that are separated by a distance equal to
21 the distance between adjacent storage elements in the
22 rows. With this arrangement, the medium can be tested for
23 defects prior to recording by scanning the surface of the
24 medium with a non-destructive laser beam and measuring the
25 reflectivity from each micromirror. The reflective and

1 absorptive capacity of the micromirror is a function of
2 the amount of coated material on the mesa, therefore, if
3 each micromirror is confirmed for reflectivity, the medium
4 can be certified for recording with a high degree of
5 assurance that the recording will be accurate. During
6 this pre-test, the physical position, as well as the
7 reflectivity, of each micromirror is verified. This may
8 be done by any desired mode of scanning in which the
9 distance between micromirrors is verified, as by a
10 counting device related to the speed of the beam scan.

11 Each micromirror 6 represents one bit of information.
12 Note that the size of each bit of information is deter-
13 mined prior to recording: it is not the recording device
14 that determines either the position or size of the infor-
15 mation bits. With this arrangement, the micromirrors 6
16 themselves provide the tracking guides for pre-testing,
17 recording, and read-out. The data can be packed with maxi-
18 mum density because no allowance is required for
19 variations in laser spot size during recording. The
20 tolerances permitted in the area of the focus of the laser
21 beam at the plane of the mirrors are thus greater than in
22 those arrangements where the position and size of each
23 recorded bit is determined by the action of the laser
24 beam. The maximum surface dimension of each micromirror
25 is preferably between 1 and 2.5 micrometers and the mini-

1 mum dimension should not be less than the wavelenqth of
2 the light being used for reading. For special applica-
3 tions, the mirror size may be less than one micrometer or
4 substantially greater than 2.5 micrometers. For most
5 applications, where density of recording is important,
6 th area of the micromirror preferably is between 0.7 and
7 about 5 square micrometers. It is preferred that the
8 distance between the mesas 6 be not significantly less
9 than the maximum surface dimension of the micromirrors.
10 The reflecting area of the micromirrors 6 may be round,
11 square, rectangular or any other desired shape. It is
12 convenient, however, to provide a regular array of
13 generally round reflecting surfaces equally spaced in
14 parallel rows, such as result from the example set forth
15 below. Each micromirror preferably has an original
16 reflectivity of at least 20% of the particular laser light
17 being used. After exposure to the laser beam to destroy
18 the reflectivity, the reflection preferably is signifi-
19 cantly less than 20% or at least significantly less than
20 the reflectivity of the original mirror surface.

21 In one system, preferred for many typical applica-
22 tions, the round micromirrors of one micrometer diameter
23 are spaced one micrometer apart and a recording laser beam
24 is arranged to scan the mirrors at a speed of about two
25 meters per second to record data at a one meqabit/second
 rate. If a higher data rate is desired, a faster scanning

1 speed can be used. The micromirrors preferably are spaced
2 as closely as possible in the array, for maximum storage
3 capacity, but the dimensions of each mirror must be large
4 enough to permit it to function as a mirror at the wave-
5 length of light being used and the micromirrors must be
6 separated by a distance great enough that neither the
7 recording or read-out laser beam can overlap two micro-
8 mirrors.

9 EXAMPLE

10 The following is an example of the steps in the
11 preparation of the recording medium embodying the
12 present invention: A photoresist relief pattern
13 comprising a square array of flat bottoms with
14 tapered peaks, with center-to-center spacing of about
15 2 micrometers (see Figures 4, 5 and 6) was prepared
16 as follows. Positive photoresist (Shipley AZ-1450J,
17 manufactured by Shipley Company, Inc. Newton,
18 Massachusetts) was spin coated on a glass plate to a
19 thickness of several micrometers. The plate was then
20 exposed to an argon laser interference pattern using
21 a glass prism to split the beam and to recombine the
22 two halves, thus forming a series of spaced parallel
23 interference lines at the photoresist target. The
24 exposure was through the glass plate so the greatest
25 exposure was at the bottom of the layer of the photo-
resist.

1 After a three-minute exposure, the plate
2 was rotated 90 degrees and exposed a second time, as
3 described by M. T. Gale in Optics Communications,
4 Volume 18, No. 3, August 1976, page 295. The plate
5 was then developed for twenty seconds in Shipley
6 developer. Figure 4 is a reproduction of a scanning
7 electron micrograph, at a magnification of 10,000X,
8 of the photoresist pattern, tilted at an angle of
9 about 45°. This micrograph shows partly etched saddle
10 points between adjacent peaks, indicating that each
11 exposure was above the threshold for development of
12 the photoresist. It shows also that at the inter-
13 section of the lines, etching of the photoresist
14 extends to the surface of the glass plate. The flat
15 surfaces thus created are important because they
16 will define the flat substrate of the reflective
17 micromirrors of the optical recording medium.

18 A nickel mold was made from the photoresist
19 plate, prepared as above. This process is described
20 in National Geographic, March 1984, page 373. A
21 second generation nickel electroform was made from
22 the original nickel master. The second generation
23 nickel had contours corresponding to those of the
24 photoresist plate and served as a stamper to repro-
25 duce the pattern by embossing sheets of plastic.

1 An array of flat-topped plastic mesas was pro-
2 duced by embossing a sheet of PVC plastic with the
3 nickel stamper, described above, in a Carver
4 Laboratory press, Model C, manufactured by Fred C.
5 Carver, Inc., Menomonee Falls, Wisconsin. The nickel
6 stamper was placed, contoured side up, on a sheet of
7 lead on the lower stage of the press. A sheet of 10
8 mil thick glossy black PVC plastic, obtained from
9 Ridout Plastics, San Diego, California, was placed
10 over the nickel stamper. The press was pumped to a
11 pressure of 20,000 pounds and the lower heating unit
12 was raised to a temperature of 250 degrees Fahrenheit.
13 The heater in the upper platen was not energized
14 while the heat from the lower unit penetrated the
15 lead, nickel and plastic. When the thermometer in
16 the upper platen read 200° F., the lower heater was
17 turned off and the 20,000 pounds pressure was main-
18 tained during cooling. When the temperature in the
19 upper unit had dropped to 150° F., the pressure was
20 released and the PVC was peeled from the nickel
21 stamper. A bright diffraction pattern was visible on
22 the embossed PVC. Figure 5 is a reproduction of a
23 scanning electron micrograph of the embossed PVC at a
24 magnification of 10,000X tilted at an angle of about
25 45°.

1 A reflective material was then coated on the
2 embossed surface of the PVC. This material was chosen
3 to be both reflective enough to permit identification
4 as a micromirror by an optical reading device and
5 also capable of absorbing sufficient laser energy to
6 melt or cause distortion of the plastic substrate
7 during data recording. The preferred material is a
8 metal and ceramic composite of gold and silicon
9 dioxide. Such materials, known as cermets, have been
10 used for thin film resistors and in light absorbing
11 applications such as solar collectors. The
12 Au-SiO₂ system is described in the Handbook of Thin
13 Film Technology, McGraw-Hill, 1983, chapter 18, page
14 21.

15 The cermet layer, coated on glossy clear
16 polyester, has about four times greater absorbancy at
17 830 nm than a pure gold layer on the same substrate.
18 The cermet is also significantly more sensitive to
19 alteration of reflectivity by laser light. A pure
20 gold layer showed no response to pulses of several
21 microseconds, at a power level of about 5 milliwatts.
22 Under the same conditions, the cermet coating showed
23 significant changes in reflectivity in response to
24 pulses of less than one microsecond.
25

1 Finally, cermet was sputter coated on the
2 embossed PVC described earlier. This storage medium
3 showed visible changes in reflectivity at pulse dura-
4 tions of less than 0.3 microseconds at the same 5
5 milliwatt power level.

6 Figure 6 is a reproduction of a photograph of a
7 sample of the recording medium comprising an array of
8 individually alterable micromirrors of
9 Au-SiO₂ on embossed PVC plastic. The photograph was
10 from a TV monitor attached to an optical system pro-
11 viding a magnification of about 1750X on the screen.
12 Some of the micromirrors in a row near the bottom
13 have been exposed to a 0.5 microsecond pulse from an
14 830 nm diode laser, at a power level of about 5
15 milliwatts. The darkened spots are clearly visible
16 as areas of significantly lower reflectivity in
17 response to the laser pulses.

18
19 In this test, the response to the recording laser
20 beam was only along the rows of micromirrors, not between
21 them. If only a portion of a micromirror is exposed to
22 the laser beam, the entire micromirror will still melt or
23 be distorted, although somewhat more slowly. These
24 properties are especially advantageous in optical data
25 recording because the recorded spot size and location is

1 less sensitive to variations in the laser spot size and
2 alignment.

3 In reading a previously recorded area of the medium,
4 it is desirable to be able to distinguish between three
5 levels of illumination: the level represented by an
6 untreated micromirror retaining its original reflectivity,
7 the level represented by a micromirror that has been
8 treated by the laser beam to destroy its reflectivity, and
9 the reflectivity represented by the valleys 10 between the
10 mesas 8. The areas between the mesas have no reflecting
11 surface in the plane of the micromirrors 6, so that the
12 reflection is reduced by dispersion of the beam at posi-
13 tions beyond the focal point of the beam. The untreated
14 areas of the medium 2 between the mesas will also have an
15 inherently lower reflectivity than the micromirrors 6 even
16 though some of the sputtered mirror coating material is
17 deposited in the valley areas. Generally, therefore, it
18 is not desirable to eliminate all reflectivity of the
19 micromirrors 6, but to reduce it only enough to make it
20 readily distinguishable from the untreated micromirrors.
21 This allows recorded micromirrors to continue to serve as
22 tracking and timing markers. In this example, the
23 unaltered micromirrors have a reflectivity greater than
24 20% at 830 nm and a laser power of about 3.2 nanojoules
25 per square micrometer is sufficient to reduce the reflec-

1 tivity of the mirror coating by the desired amount. Other
2 kinds or quantities of mirror coatings can be used that
3 require higher recording energy, but it is preferable
4 that the micromirror be destroyed by exposure to focused
5 energy no greater than 200 nanojoules per square micro-
6 meter.

7 It is important to provide a mirror surface that is
8 relatively immune to oxidation or discoloration or dulling
9 from other causes. It is important also, to provide a
10 surface that is affected only minimally by dust or other
11 contaminants. For those reasons, a layer of transparent
12 material, generally indicated at 12 in Figure 7, is posi-
13 tioned over the surface of the mesas 8. This layer, which
14 may be formed of polyester, polycarbonate or other
15 transparent plastic, is in contact with the micromirrors 6
16 and is of substantial thickness (100 or more times the
17 height of the mesas 6) so that, during recording and read-
18 out by a laser beam focused on the micromirrors 6, the
19 converging laser beam covers a significant area at the
20 point where it enters the layer 12 and so minimizes the
21 effect of a dust particle on the surface of the layer 12.

22 A filler 14, which may be a liquid such as oil, fills
23 the valleys 10 and displaces any air that would otherwise
24 be trapped between the micromirror surfaces and the layer 12.
25 The liquid is preferably selected with an index of refrac-

tion near that of the plastic from which the layer 12 is formed to avoid any undesirable reflection of the laser beam. The filler 14 may remain as a liquid or it may be composed of a liquid plastic accompanied by a catalyst so that after the filler is in position the plastic solidifies. Alternatively the filler may be a UV curable polymer. With any of the filler compositions, it is desirable to add an infrared absorbing dye to the filler to further reduce any reflection from the valleys 10. Such dyes are well known in the prior art.

In general, the recording of data by altering the reflectivity of selected micromirrors results in each micromirror having only one of two possible states, that is, the micromirror reflects the incident light as a mirror or has a reflectivity below some predetermined level and is not considered to be a mirror. The density of information storage can be increased by providing for additional levels of reflectivity. For example, each original micromirror 6 can be constructed to have a reflectivity of 40-45% at the frequency of the laser beam used for readout. A first level of intensity of the laser recording beam may be adjusted so that during the time of recording on one micromirror, the reflectivity is reduced to between 25% and 35%. To record another state, the intensity of the recording laser beam is increased suf-

1 ficiently that during the time of exposure the reflec-
2 tivity is reduced to between 10% and 20%. A single micro-
3 mirror can thus be used to store any one of three infor-
4 mation indicia: (1) the mirror retains full reflectivity,
5 that is, between 45% and 55%; (2) the reflectivity is
6 between 25% and 35%; and (3) the reflectivity is between
7 10% and 20%. The valleys 10 should have a reflectivity
8 substantially less than 10% to permit even the micro-
9 mirrors with minimum reflectivity to be used as timing and
10 tracking guides.

11 In an alternative embodiment, the recording medium
12 and the overlying plastic protective sheet are fabricated
13 as an integral structure. As illustrated by Figure 8, the
14 stamper used to form the medium 2a is the reverse of the
15 one used to form the medium of Figures 1-3. In this
16 instance, the mesas 8a are formed as depressions in a
17 first surface 16 of a substrate 4a formed of clear ther-
18 moplastic. The micromirrors 6a are formed by exposing the
19 surface containing the indentations to the sputtering
20 action of the mirror coating. The micromirrors 6a are
21 therefore formed on the flat surfaces at the bottoms of
22 the indentations. However, viewed from the opposite side,
23 in the direction of the arrow 18, the indentations appear
24 as mesas with the mirror coating on the flat tops.

1 The micromirrors 6a are exposed to the recording and
2 reading laser beams, in the direction of the arrow 18,
3 through the plastic substrate 4a. With this arrangement,
4 the micromirrors 6a are in intimate contact with substrate
5 material providing superior protection of the reflecting
6 surfaces from contamination. One additional advantage of
7 this construction is that, in the process of fabrication,
8 reflective material that is inevitably sputtered onto the
9 exposed surface 16 of the substrate 4a, which forms the
10 bottoms of the valleys 10a, may be completely removed by
11 abrading. The bottom surface of the substrate 4a between
12 the indentations may be provided with a layer of light
13 absorbent material thereby rendering the valleys 10a
14 between the micromirrors substantially non-reflective.
15 The plastic material of the substrate 4a now replaces the
16 layer 12 that is a separate entity in the earlier embodi-
17 ment. The plastic is continuous from the surface exposed
18 to the laser beam to the bottom of the valleys 10a at the
19 surface 16 with no disruptive reflections resulting from a
20 change in the index of refraction.

21 One scanning procedure for recording on and reading
22 from either of the embodiments of the medium 2 and 2a is
23 illustrated by Figures 1 and 9. A source of coherent
24 light, such as a diode laser 22, produces a beam 24, that
25 is first made more uniform by a collimating lens and an

1 anamorphic prism, both indicated diagrammatically at 16,
2 and then is focused through an objective lens 32 onto the
3 micromirrors 6. The maximum dimension of the beam in the
4 plane of the mirrors, indicated by the broken line 28, is
5 preferably no greater than the cross-sectional area of
6 each individual mirror, and in any event small enough to
7 distinguish one micromirror from any adjacent micromirror.
8 The same optical system is used for both recording and
9 reading. The laser light reflected from the micromirrors
10 is directed by a beam splitter 20 to an optical detector,
11 generally indicated at 36.

12 One method for scanning the medium 2 is to cause the
13 laser beam to traverse one row of micromirrors from one
14 end of the medium 2 to the other. At the end of each row,
15 the laser beam is caused to move to the next row of micro-
16 mirrors and to scan that row in the opposite direction.
17 As illustrated in Figure 1, a first row of micromirrors is
18 scanned along line "a" from one end of the medium to the
19 other. The scanning beam is then moved sideways to the
20 next row and scans along line "b" in the reverse direc-
21 tion. The beam is then again moved sideways and the
22 micromirrors scanned along line "c". A preferred proce-
23 dure, however, is to scan the micromirrors diagonally as
24 illustrated by Figure 10 which provides an improved signal
25 to noise ratio by increasing the distance between suc-

1 cessive micromirrors. The equally spaced rows of micro-
2 mirrors that make up the regular array are represented by
3 the broken lines "d" and "e". The scanning track of the
4 laser beam 24, however, is successively along lines "f",
5 "g" and "h" which are diagonal with respect to the
6 parallel rows of micromirrors, such as "d" and "e", forming
7 the regular array. At the end of row "f", the scanning
8 motion is interrupted and moved sideways in the direction
9 of the arrow "j" to place the row "g" in scanning posi-
10 tion. The laser beam then scans that row in the reverse
11 direction along the line "g". This process is repeated to
12 scan the entire series of rows over the entire surface of
13 the medium. An end-of-row code is pre-recorded on each
14 row and is read by the recording and reading systems to
15 cause the scan to move to the next row of micromirrors at
16 the appropriate point.

17 The scanning movement along the rows may be
18 accomplished by moving either the entire laser and optics
19 assembly or by moving the medium 2. In this example,
20 because the mass of the medium 2 is only a fraction of
21 that of the laser-optics assembly, there is substantial
22 advantage in moving the medium. The reciprocating
23 scanning action, which results in variations in the
24 scanning velocity, is made practical by the regular
25 arrangement of the micromirrors which can be used to

control the timing both during recording and read-out.

The transverse movement, to move the beam from one row of micromirrors to the next, is preferably accomplished by a sideways movement of the laser 22 and the associated optics at the end of the scanning of each row of micromirrors. The sideways movement may also be accomplished by movement of the medium, by deflection of the laser beam, or by a combination of the two. For example, the laser beam may be deflected, by means well known in the art, to accomodate the scanning of a pre-selected number of rows and then the medium moved sideways by a similar number of rows while the beam deflection is returned to its original position.

During the scanning, the position of either the laser beam or the medium 2, or both, are controlled by the use of the micromirrors as tracking guides. During the scanning of each row of micromirrors, the beam 14 is caused to oscillate transversely, at a frequency much lower than the data rate, by a galvanometer-actuated mirror, or other means well known in the art, for a distance at the point of focus somewhat less than the distance across one micromirror. The transverse sweep of the scanning action is indicated by the broken lines 38 and 42 in Figure 11 as the scan proceeds along the centerline "k". The magnitude of the transverse scan depends

1 upon the size of the micromirrors, the size of the
2 scanning spot, and the distance between adjacent micro-
3 mirrors. The intensity of the reflected light is averaged
4 by a tracking control mechanism, which forms part of the
5 optical detector 36, over a substantial number of micro-
6 mirrors before changing the direction of oscillation, in
7 order to improve the tracking precision. The tracking
8 control mechanism maintains the beam 24 centered on the
9 row of micromirrors being scanned. If the average inten-
10 sity of the reflected beam when it is deflected, say, to
11 the right, as diagrammatically illustrated at 44, is less
12 than the average intensity when deflected an equal
13 distance in the opposite direction, the beam 24 is
14 adjusted toward the left to move it nearer the center line
15 of the micromirrors. If desired, the area of the beam 24
16 in the focus plane may be made slightly larger than the
17 reflecting area of one micromirror, so long as it is small
18 enough that it cannot encompass any substantial fraction
19 of two mirrors at the same time, so that it can detect the
20 reflectivity of each micromirror despite small misalign-
21 ment of the read-out beam relative to the centerline of
22 the row of micromirrors being scanned.

1 Prior to recording, the medium 2 is scanned by the
2 laser beam 24 at low intensity to determine whether all or
3 substantially all of the micromirrors have the requisite
4 reflectivity. After the medium has been certified as free
5 from defects, or the defects "fenced off" as described
6 below, the permanent recording is made by the laser beam
7 24 which has a first level of intensity sufficient to
8 enable the optical detector 36 to determine the presence
9 of a reflecting micromirror 6 on the surface of a mesa 8,
10 and a second level of intensity great enough to destroy
11 the reflectivity of the micromirror at which it is
12 directed. The intensity of the laser beam 24 is modulated
13 as the recording is made to destroy the reflectivity of
14 the mirrors in accordance with the information to be
15 recorded.

16 The laser beam 24 operates at its low or reading
17 intensity until the detector 36 indicates the beam is
18 focused on a micromirror. If the digital information to
19 be recorded indicates that particular micromirror is to be
20 destroyed, the laser beam is pulsed to its higher
21 recording intensity for a period of one microsecond or
22 less, but long enough to destroy the micromirror. If that
23 particular micromirror is not to be destroyed, the laser
24
25

1 beam passes over it at the lower non-destructive intensity
2 leaving the reflectivity of the micromirror unchanged.

3 By destruction of the reflectivity is meant a
4 lowering of the reflectivity by an amount sufficient that
5 the optical detector 36 can determine the difference
6 between a micromirror that has been exposed to the laser
7 beam 24 at recording intensity from one that retains its
8 original reflectivity.

9 If the examination of the medium prior to recording
10 indicates relatively few defects, the rows of micromirrors
11 containing defects can be "fenced off", that is, the par-
12 ticular rows containing defects are marked with a special
13 code that causes the scanning mechanisms used in both
14 recording and reading to jump immediately to the suc-
15 ceeding row and omit scanning the defective areas of the
16 medium. So long as the number of defects is limited, the
17 loss in recording capacity is not significant. In
18 addition, error-correcting codes which, in effect, record
19 data in a redundant manner in different areas can be used
20 to overcome defects in the recording medium.

21 In the examples detailed here, the medium is in the
22 form of a small rectangular card, no more than 10-15 mils
23 thick, well suited for reciprocal scanning modes.
24 However, the recording array may be in the form of a drum,
25 disk or tape and the scanning mode may be either recipro-

1 cating or continuous. The recording medium may be formed
2 as a flat medium and then secured to a rotatable drum, or
3 otherwise altered in shape, for recording and read-out.
4 The reference plane of the medium, that is, one of the
5 exposed surfaces, is considered to be parallel with the
6 plane of the micromirrors even though both surfaces may be
7 curved so long as the two planes are the same distance
8 apart at all points.

9
10 CLAIMS:
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1 1. A system for recording digital information comprising
2 a recording medium having

3 a substrate, and

4 a substantially regular array of spaced,
5 discrete, immediately detectable alterable storage ele-
6 ments, each capable of recording at least one bit of digi-
7 tal information,

8 a laser beam source capable of sufficient intensity
9 to immediately alter a storage element of said medium
10 exposed to said beam,

11 scanning means arranged to focus said laser beam on
12 individual storage elements of said medium, and

13 modulation means arranged to modulate said beam in
14 accordance with the digital information to be recorded.
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1 2. The system as claimed in Claim 1 wherein
2 said scanning means is arranged to focus said beam
3 successively on the individual storage elements, and
4 said modulation means is arranged to change the
5 intensity of said beam between two levels of intensity in
6 accordance with the information to be recorded, one of
7 said levels being of sufficient intensity to produce an
8 immediately detectable alteration of one of said storage
9 elements as a result of exposure to scanning by said
10 scanning beam, and the other of said levels being of an
11 intensity that causes no significant alteration in a
12 storage element as a result of exposure to said laser beam
13 during scanning.

14
15 3. The system as claimed in Claim 1 wherein
16 said laser beam source is a diode laser.

17
18 4. The system as claimed in Claim 1 wherein
19 each of said storage elements is a flat micromirror.
20
21
22
23
24
25

1 5. The system as claimed in Claim 1 wherein
2 said substrate is a sheet of transparent ther-
3 moplastic having in a first surface thereof a regular
4 array of spaced indentations, and wherein
5 each of said storage elements is on the bottom of one
6 of said indentations.

7
8 6. The system as claimed in Claim 1 wherein
9 each of said storage elements is a micromirror sup-
10 ported by thermoplastic material and in which
11 said alteration is the result of heat deformation of
12 said thermoplastic material.

13
14 7. The system as claimed in Claim 6 including
15 a plurality of spaced, discrete projections extending
16 from one surface of said thermoplastic material and each
17 supporting one of said micromirrors.

18
19 8. The system as claimed in Claim 6 wherein
20 each of said micromirrors has a maximum surface
21 dimension between about one and 2.5 micrometers.

22
23 9. The system as claimed in Claim 6 wherein
24 the reflectivity of each of said micromirrors in the
25 unaltered state is at least 20 percent.

1 10. The system as claimed in Claim 6 wherein
2 each of said micromirrors comprises a metal-
3 containing film.
4

5 11. The system as claimed in Claim 6 wherein
6 said medium comprises
7 a sheet of plastic having formed integrally
8 therewith a regular array of spaced mesas each supporting
9 one of said micromirrors, each of said micromirrors being
10 capable of being destroyed by a single pulse of focused
11 energy less than 200 nanojoules per square micrometer
12 thereby to become a depository for one bit of digital
13 information.
14

15 12. The system as claimed in Claim 6 wherein
16 in the unaltered state each of said micromirrors has
17 a reflectivity between 20 and 55 percent, and in the
18 altered state has a reflectivity substantially less
19 than in the unaltered state, the number and location of
20 said micromirrors having a reduced reflectivity being a
21 function of the digital information recorded on the
22 medium.
23
24
25

1 13. The system as claimed in Claim 6 wherein
2 said micromirrors are arranged in parallel rows
3 forming a regular array, and
4 said scanning means is arranged to scan said rows
5 successively in opposite directions.
6

7 14. A system as claimed in Claim 13 wherein
8 said scanning means is arranged to scan along
9 parallel paths diagonal to said rows.
10

11 15. The system as claimed in Claim 13 wherein
12 each of said micromirrors is a metal-containing film
13 having

14 a reflectivity of at least 20 percent and a maximum
15 surface dimension between about one and 2.5 micrometers.
16

17 16. The system as claimed in Claim 15 wherein
18 said substrate has a reference surface, and
19 a regular array of spaced mesas extending from said
20 surface, each supporting one of said micromirrors.
21

22 17. The system as claimed in Claim 16 wherein
23 said medium includes a transparent layer overlying
24 and in intimate contact with said micromirrors.
25

1 18. A medium for recording digital information comprising
2 a substrate having
3 an array of spaced discrete storage elements,
4 each of said storage elements being individually
5 capable of immediately detectable alteration by exposure
6 to a single pulse of focused energy of less than 200 nano-
7 joules per square micrometer thereby to become a deposi-
8 tory for one bit of digital information,

9 the specific area of each storage element subject to
10 such alteration by said focused energy being pre-defined
11 prior to the exposure to such energy.
12

13 19. The medium as claimed in Claim 18 wherein
14 said substrate is formed of transparent material
15 having therein a regular array of spaced depressions of
16 uniform depths extending inwardly from one plane thereof,
17 and

18 each of said storage elements comprises a micromirror
19 covering the bottom of one of said depressions.
20

21 20. The medium as claimed in Claim 18 wherein
22 each of said elements is a micromirror, and
23 said micromirrors are arranged in a regular array.
24
25

1 21. The medium as claimed in Claim 20 wherein
2 the minimum distance between said micromirrors is not
3 significantly less than the maximum surface dimension of
4 said micromirrors.

5
6 22. The medium as claimed in Claim 20 wherein
7 each of said micromirrors has an area between about
8 0.7 and four square micrometers.

9
10 23. The medium as claimed in Claim 20 wherein
11 substantially all of said micromirrors in its origi-
12 nal unaltered state has a reflectivity of at least 20% at
13 830nm.

14
15 24. The medium as claimed in Claim 20 wherein
16 said substrate comprises a flexible thermoplastic and
17 including
18 a plurality of mesas formed integrally with said
19 substrate and each supporting one of said micromirrors,
20 said mesas defining a plurality of valleys therebetween.

21
22 25. The medium as claimed in Claim 20 wherein
23 each of said micromirrors is formed of a metal-con-
24 taining film.

25

1 26. The medium as claimed in Claim 25 wherein said film
2 is a composite of a metal and a silicate.

3
4 27. The medium as claimed in Claim 26 wherein
5 said film is a composite of gold and silicon dioxide.

6
7 28. The medium as claimed in Claim 20 including
8 a plurality of spaced discrete mesas extending from
9 said reference surface, each supporting one of said micro-
10 mirrors, and wherein
11 each of said micromirrors is formed of a metal-
12 containing film.

13
14 29. The medium as claimed in Claim 20 wherein
15 each of said micromirrors has a maximum dimension no
16 greater than about one micrometer.

17
18 30. The medium as claimed in Claim 24 wherein
19 the reflectivity of said micromirrors in both the
20 altered and unaltered state is greater than the reflec-
21 tivity from said valleys.

22
23 31. The medium as claimed in Claim 29 wherein
24 each of said micromirrors has an area no greater than
25 about five square micrometers.

1 32. the method of recording digital information
2 comprising the steps of

3 providing a substrate,
4 supporting from said substrate, discrete, spaced
5 storage elements,

6 each of said storage elements being capable of
7 immediately detectable alteration by exposure to focused
8 energy, and

9 exposing, in accordance with digital information to
10 be recorded, selected storage elements to a source of
11 focused energy of sufficient intensity to produce an
12 immediately detectable alteration in each of said selected
13 storage elements,

14 each of said storage elements defining, prior to
15 exposure to said focused energy, a specific area subject
16 to alteration thereby.

17
18 33. The method as claimed in Claim 31 wherein

19 each of said storage elements is a micromirror and
20 including the step of

21 arranging said micromirrors in a plurality of spaced
22 parallel rows.
23
24
25

1 34. The method as claimed in Claim 33 wherein
2 said selected micromirrors are exposed to said
3 focused energy successively along each of said rows, the
4 direction of movement of said exposure being reversed on
5 successive rows.

6
7 35. The method as claimed in Claim 33 wherein said micro-
8 mirrors are arranged in a substantially regular array.

9
10 36. The method as claimed in Claim 33 wherein
11 said exposure to said focused energy is successively
12 along parallel paths diagonal to said rows.

13
14 37. The method as claimed in Claim 36 including the step
15 of
16 supporting each of said micromirrors on a discrete
17 mesa extending from said reference surface, each of said
18 mesas being separated by intervening valleys from adjacent
19 mesas.

20
21 38. The method as claimed in Claim 37 wherein
22 said medium is formed predominately of thermoplastic
23 material.

1 39. The method as claimed in Claim 38 wherein
2 said focused energy is a laser beam,
3 and said exposure comprises the step of
4 focusing said laser beam on said selected micro-
5 mirrors thereby to destroy the micromirror and thereby
6 record one bit of digital information.

7
8 40. The method of making and pretesting a digital
9 recording medium comprising the steps of
10 forming a substrate of thermoplastic material having
11 thereon a regular array of spaced, separate predefined
12 information storage areas,
13 coating each of said areas with a reflective coating
14 thereby to form a regular array of optically alterable
15 micromirrors,
16 successively scanning each of said micromirrors with
17 a laser beam having an intensity less than that which will
18 significantly reduce the reflectivity of said micro-
19 mirrors, and
20 measuring the light reflected from each micromirror
21 and comparing it with a predetermined level of reflec-
22 tivity thereby to detect defects in the reflectivity of
23 said micromirrors.
24
25

1 41. The method of recording digital information

2 comprising the steps of

3 providing a substrate of thermoplastic material,
4 depositing on said substrate a plurality of parallel
5 rows of spaced, discrete, optically-alterable micro-
6 mirrors, and

7 scanning along paths diagonal to said rows with a
8 laser beam modulated, in accordance with digital infor-
9 mation to be recorded, between two levels of intensity,
10 the higher of said intensities being great enough to
11 destroy the reflectivity of one of said micromirrors by
12 exposure thereto during the scanning.

13
14 42. The method of making a medium for the storage of
15 digital data comprising the steps of

16 providing a substrate of transparent thermoplastic
17 material having first and second opposing surfaces,

18 forming in said first surface a substantially regular
19 array of spaced depressions,

20 depositing a reflecting coating on said first surface
21 and on the bottom of each of said depressions, and

22 removing said reflective coating from the exposed
23 areas of said first surface between said depressions.

24

25

1 43. The method as claimed in Claim 42 wherein
2 said coating on said first surface is removed by
3 abrasion.

4 44. The method as claimed in Claim 42 including the step
5 of
6 applying a non-reflecting layer to said areas of said
7 first surface between said depressions.
8

9 45. A digital recording medium comprising
10 a transparent thermoplastic substrate having first
11 and second opposing surfaces,
12 said first surface having therein a substantially
13 regular array of spaced depressions,
14 a plurality of optically-alterable micromirrors each
15 formed on the bottom of one of said depressions,
16 each of said micromirrors being capable of reflecting
17 at least 20 percent of laser light focused upon it through
18 said second surface of said substrate.
19

20 46. The medium as claimed in Claim 45 wherein
21 each of said micromirrors is capable of being
22 destroyed by laser beam having an energy level less than
23 200 nanojoules.
24
25

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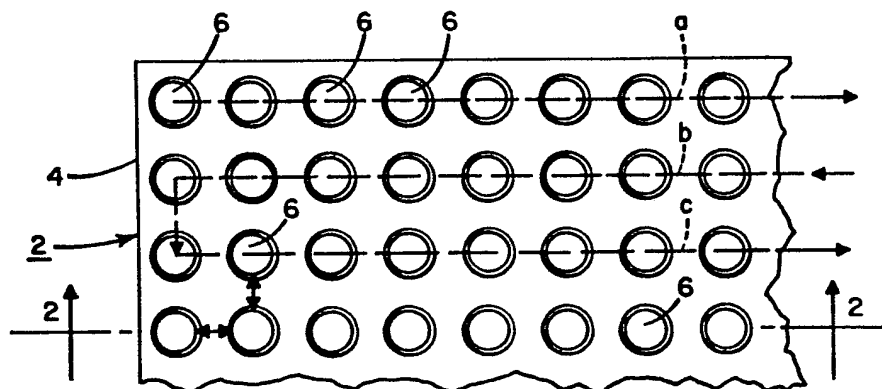


Fig. 1.

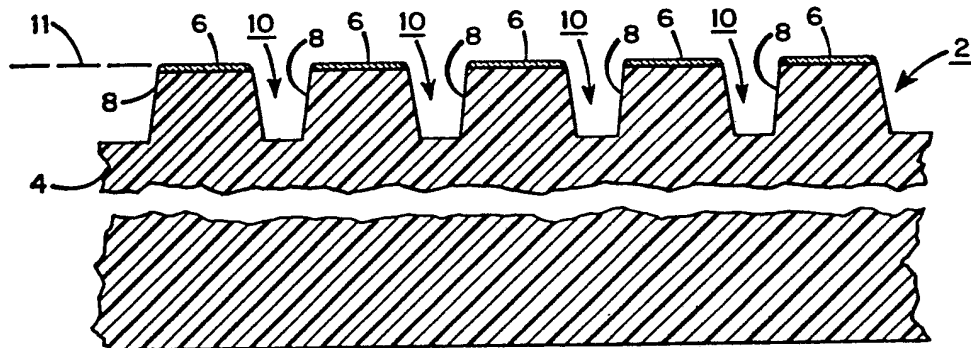


Fig. 2.

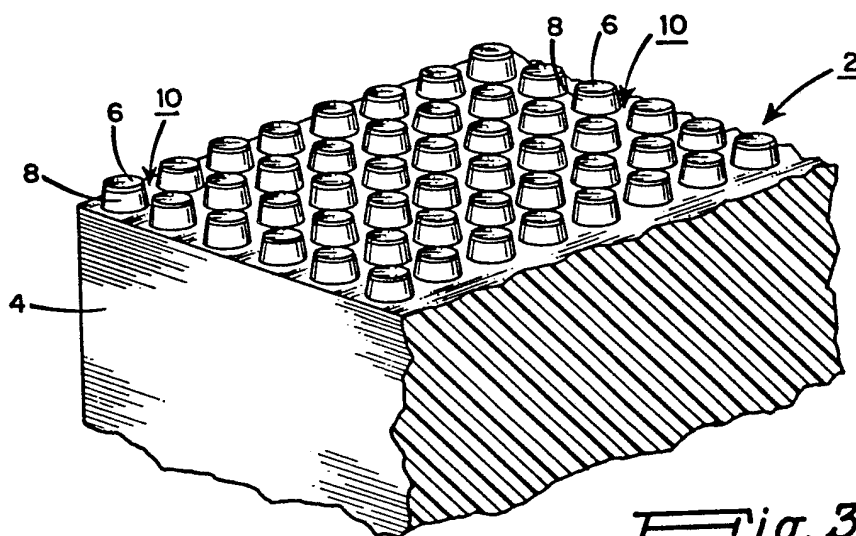


Fig. 3.

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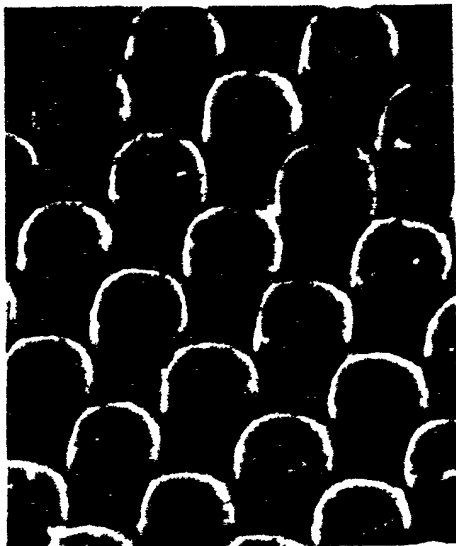


Fig. 4.

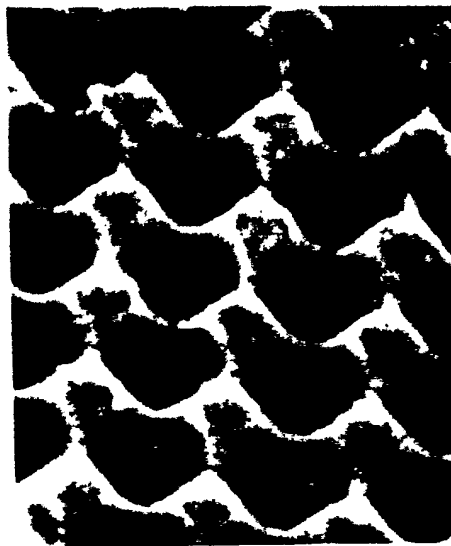


Fig. 5.

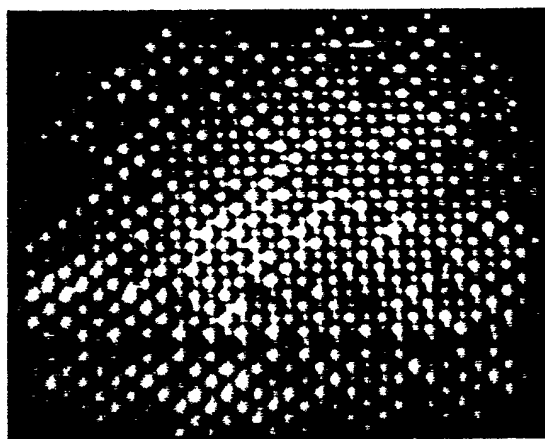


Fig. 6.

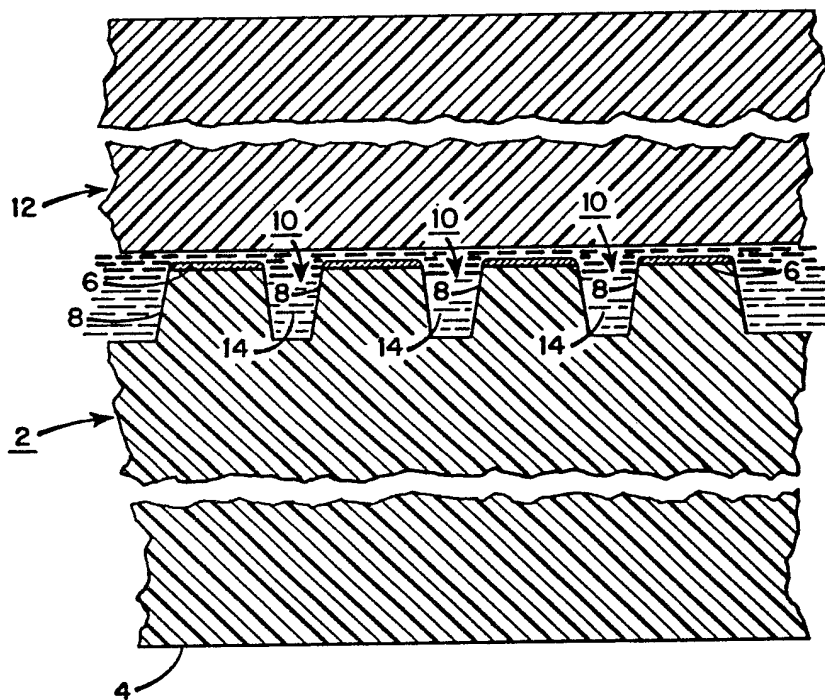


Fig. 7.

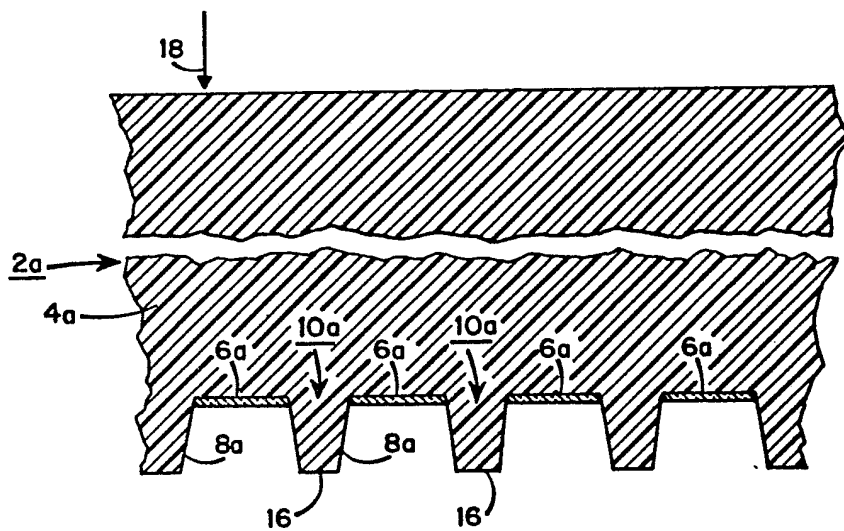


Fig. 8.

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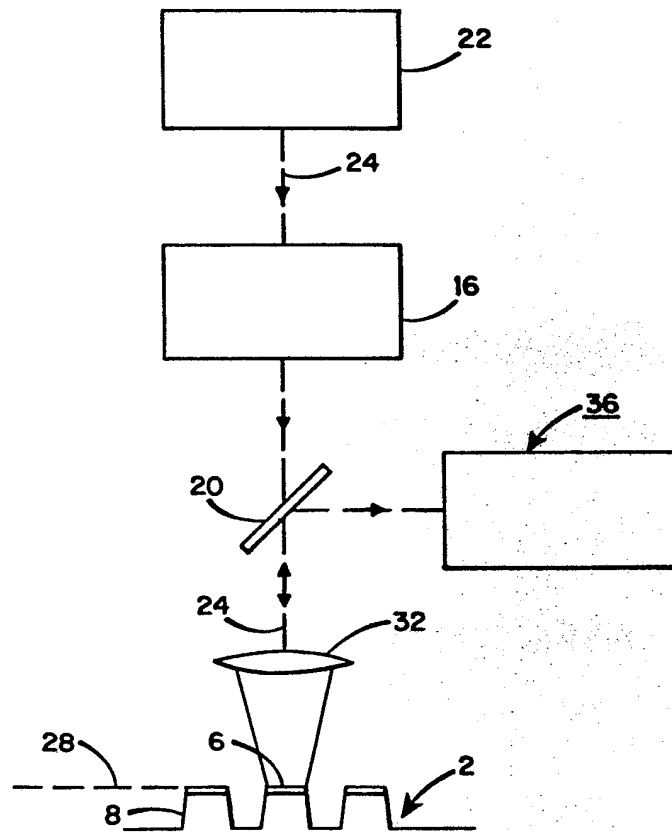


Fig. 9.

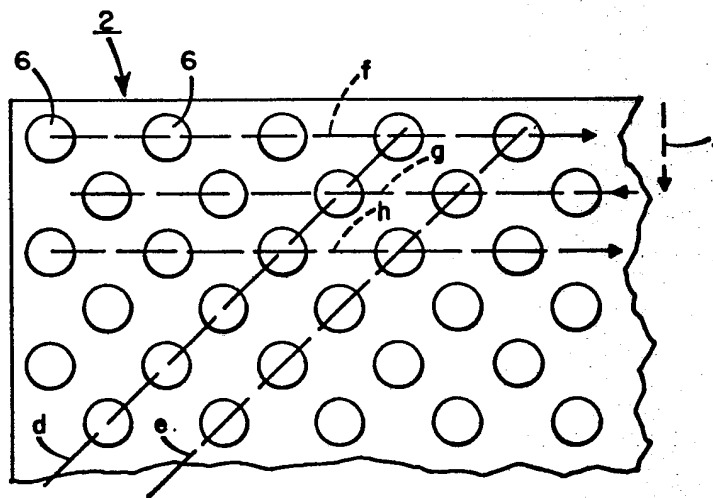


Fig. 10.

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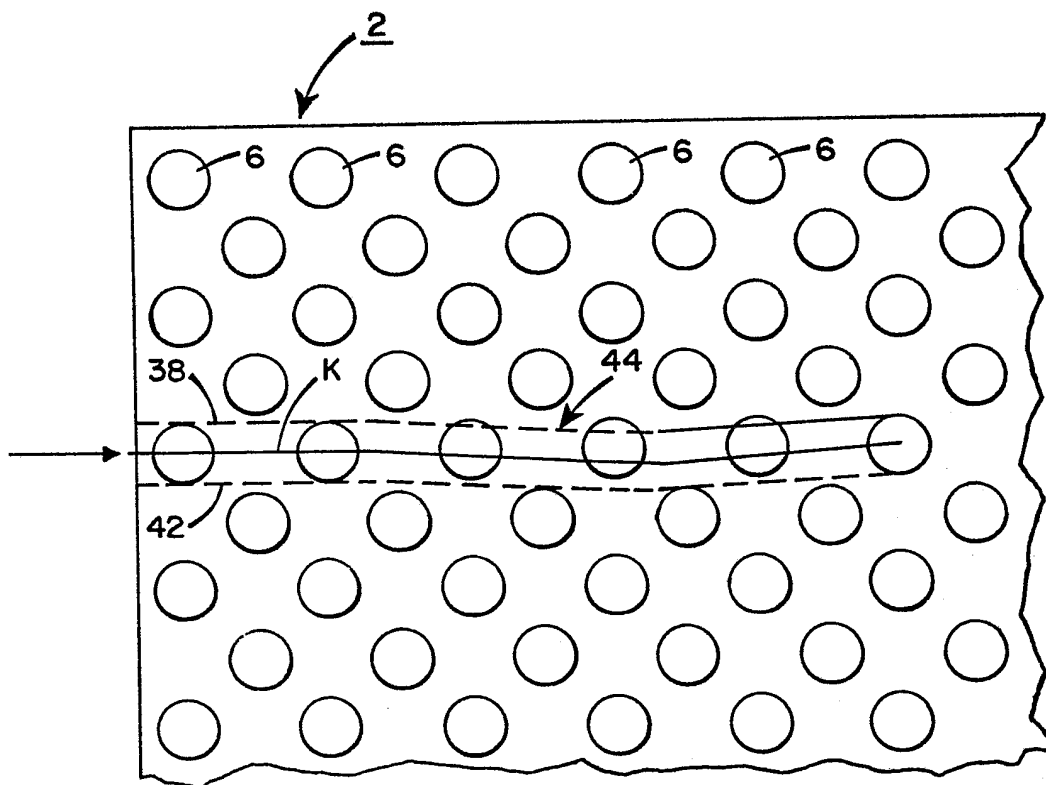


Fig. 11.